A 2.5-2.7 THz Room Temperature Electronic Source

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Abstract—**We report on a room temperature 2.5 to 2.7 THz electronic source based on frequency multipliers. The source utilizes a cascade of three frequency multipliers with W-band power amplifiers driving the first stage multiplier. Multiple-chip multipliers are utilized for the two initial stages to improve the power handling capability and a sub-micron anode is utilized for the final stage tripler. Room temperature measurements indicate that the source can put out a peak power of about 14 microwatts with more than 4 microwatts in the 2.5 to 2.7 THz range.**

Index Terms—**Frequency multipliers, Schottky diode multipliers, Submillimeter-wave technology, Power combining, Varactor diodes.**

I. INTRODUCTION

SUBMILLIMETER-WAVE spectrometry is a proven flight technique that is essential for NASA's unique goals, such as atmospheric remote sensing, study of cosmic water profiles, comet characterization [1], and investigation of cosmological phenomena with radio telescopes [2]. Recent results obtained from the Heterodyne Instrument for Far-Infrared (HIFI) on the Herschel Space Observatory have shown spectacular emission and absorption spectra with unprecedented resolution [3]. The highest frequency band on HIFI is 1.9 THz. High-resolution radiometry beyond this range has been severely limited due to the lack of robust sources.

In this paper we will briefly discuss the development and characterization of a x3x3x3 based frequency multiplier chain that provides microwatts of output power in the 2.5 to 2.7 THz range. The target for our LO subsystem development is the 2.7 THz ground-state transition in HD, a molecule with immense

cosmological significance. Deuterium is formed in the Big Bang, and because of its relatively weak nuclear binding, its abundance provides strong constraints on the physical conditions during the first few minutes of the universe's expansion and hence the density of baryons [4]. Subsequently, deuterium is lost during nucleo-synthesis when material is cycled through stars in the course of galactic chemical evolution. Understanding the abundance of deuterium is essential for probing the origin and evolution of the universe as well as its star formation history. In the molecular interstellar medium deuterated molecular hydrogen is the dominant reservoir of deuterium [5]. Spectroscopic measurements of the ground-state transition of HD (at 112 µm, 2.675 THz) should allow us to make a census of deuterium in our Galaxy. Although an instrument on the Infrared Space Observatory (ISO) already detected the transition of HD in emission with low spectral resolution [6], HD can exist in a variety of regions having different densities and temperatures, so high-velocity resolution heterodyne observations are the only way to be certain of where any HD seen in absorption or emission is located.

II. DESIGN ARCHITECTURE

Schottky diode based multipliers have proven to be an excellent choice as local oscillators in the submillimeter-wave range due to their compactness, electronic tenability and stability. The approach used for the HIFI instrument was based on single chip frequency multipliers cascaded together. However, to reach 2.7 THz with enough power to pump HEB
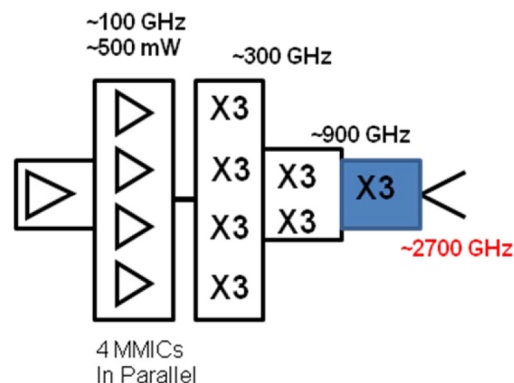

Fig. 1: Block diagram of the 2.5-2.7 THz source is shown. A scheme utilizing in-phase power combining is used to generate power at the 900 GHz driver stage, allowing for sufficient pump power to the last stage tripler.

mixers a slightly different approach, consisting of using more powerful driver stages, has been utilized. The resulting scheme used for the 2.5 to 2.7 source is shown in Fig. 1.

A. W-Band Power amplifiers

In order to have sufficient drive power at ~900 GHz we start with a ~500 mW source at ~100 GHz. While a number of recent results have been presented with GaN based power amplifier chips that can produce these power levels [7], we utilized GaAs based HEMT device power amplifiers. A four-chip waveguide based block was designed and fabricated. 90-degree quadrature hybrid couplers are utilized at the input and output of this construction. The drain voltages for each MMIC are tied together and the resultant output power as a function of frequency for different drain voltages is shown in Fig. 2.
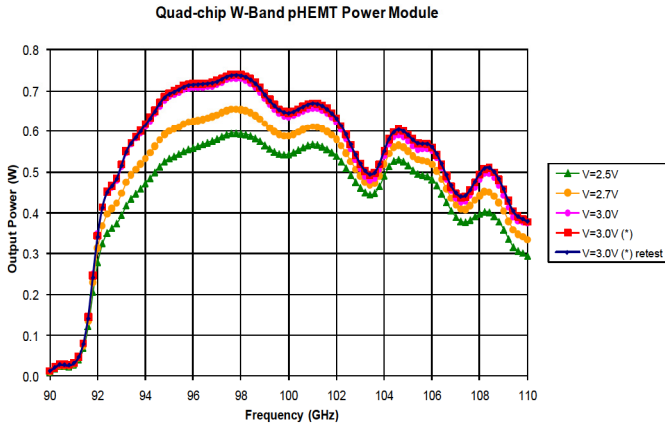

Quad-chip W-Band pHEMT Power Module

Fig. 2: Measured performance of a four-chip power combined power amplifier module as a function of various drain voltages.

B. Power-Combined Multipliers

The large amount of available power at W-band now puts the onus on the multiplier designer to successfully harness this power. A number of approaches have been identified to achieve this goal. For a given multiplier design, as the input power is increased, the multiplier will either experience thermal heating or reverse breakdown, both of which will result in catastrophic failure. To improve the thermal handling of multiplier chips, an approach based on utilizing diamond substrates has been previously reported [8]. The second limitation to frequency multiplier power-handling occurs when the input signal to the multiplier becomes large enough to drive the diodes into reverse breakdown. Increasing anode area, increasing the number of anodes per chip, optimizing doping levels, and moving to a high thermal conductivity substrate or GaN will allow additional improvements in single-chip power handling.

However, chip thickness and number of anodes per chip can only be increased up to a limit. In order to avoid unwanted waveguide modes, both of these design parameters are eventually constrained. Enhancing power handling capabilities beyond this point requires novel approaches such as

sandwiching dual chips within a single-waveguide, as suggested in [9]. A simpler to implement approach is to power combine multiplier circuits in a waveguide based topology [10]. This approach offers a number of advantages: It is a straightforward concept and does not require any new technology development at the chip level; in fact, existing chips can be utilized. The power combining and dividing functionality is accomplished in the waveguide, allowing for a low-loss transmission media. Moreover, this approach provides an easily scalable design, both in frequency as well as in power. Traditional designs such as the Y-junction and the 90-degree hybrid couplers have been utilized for this approach.

A quad-chip power combined tripler has been designed and characterized for this task, as shown in Figure 3. The power-combined version is based on two mirror-image tripler chips that are power-combined in-phase in a single waveguide block using a compact Y-junction divider at the input waveguide and a Y-junction combiner at the output waveguide. The complete power-combined tripler was designed using the methodology presented in detail in [11].
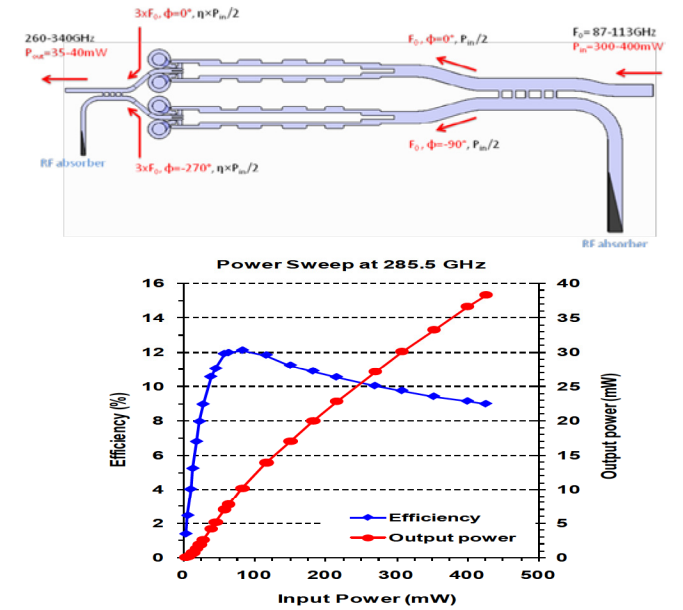

Power Sweep at 285.5 GHz

Fig. 3: Approach used to power combine four tripler chips in the first stage multiplier is shown above. The results obtained from such a quad-chip tripler are shown in the plot below for a fixed frequency of 286.6 GHz. This measurement is done at room temperature.

Fig. 3 shows an overall schematic view of the tripler including the input matching circuit. The tripler uses a split-block waveguide design with four independent DC bias lines. The input waveguide is split in four ways by a hybrid coupler followed by a Y-junction to evenly feed four multiplying circuits featuring six Schottky planar varactor diodes of about 16 fF each. The chips are mounted in four independent channels that run between their respective input and the output waveguides. The four reduced-height output waveguides are combined by a Y-junction and a hybrid coupler using the same

concept as at the input level.

On each chip, an E-plane probe located in the input waveguide couples the signal at the input frequency to a suspended microstrip line. This line has several sections of low and high impedance used to match the diodes at the input and output frequencies and to prevent the third harmonic from leaking into the input waveguide. The third harmonic produced by the diodes is coupled to the output waveguide by a second E-plane probe. In order to balance the circuit, the dimensions of both the channel and the circuit are chosen to cut off the TE-mode at the second (idler) frequency and third harmonic within the channel. The dimensions of the output waveguide ensure that the first and second harmonics are cut off at all frequencies measured, and the balanced geometry of the chips ensures that powers at the even harmonics of the input are strongly suppressed outside the diode loop. The output power achieved from this chip is shown in Fig. 3 as a function of input power. As can be seen, this provides sufficient pump power to drive the second stage multiplier for the 2.7 THz LO subsystem.

The second stage tripler, designed to cover the 850-970 GHz range, uses a similar power combining technique based on a dual-chip configuration. Details of the 900 GHz chip and chain have been presented previously [12]. The final stage tripler is based on a single balanced tripler configuration that has been successfully demonstrated in the THz range. The chip is fabricated on a very thin membrane to reduce parasitic loading. A close-up of the chip inside the waveguide block is shown in Fig. 4.

III. MEASUREMENTS

A. Test Setup

A commercial synthesizer followed by an active sextupler and a WR10 isolator is used to drive the power amplifier module. This serves as the driver for the LO chain as shown in Figure 1. The chain to 900 GHz was first calibrated and has been described in detail elsewhere [12]. When pumped with 330-500 mW at W-band, this driver chain delivers more than 1 mW in the 840-900 GHz band at room temperature as shown in Figure 5. However, for most of the tests presented in this paper, the input power at W-band was limited to 350 mW. Thus the power delivered by the driver chain to the last stage multiplier was in the range of 0.25-1 mW.

A VDI-Erickson PM4 power meter was used to record output power levels. Golay cells and cryogenic semi-conductor bolometers were also initially used to fine tune the LO chain as they provide a much faster time constant. However their calibration is more problematic, requiring an external calibrator to determine the responsivity of the sensor. The Thomas Keating power meter is easier to calibrate, but is limited to power levels above about 5 μW due to its high level of noise. In addition, the Thomas Keating meter has a large optical window, which is prone to pick up parasitic signals coming from lower-frequency leaks in the local oscillator chain (same as the Golay cell and bolometers).

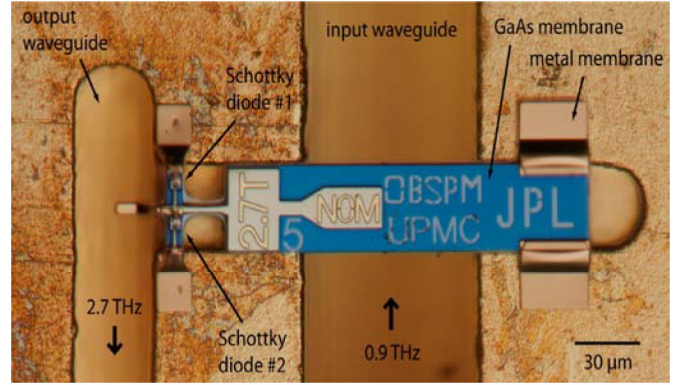The VDI-Erickon PM4 meter has the advantage of a wave-

Fig. 4: Close-up of the last stage tripler circuit. This chip design is based on a balanced tripler configuration successfully used in the THz range.

guide coupling that shields the THz signal from any lower-frequency parasitic radiation. The WR10 input waveguide is oversized for THz frequencies, so a small THz horn is used to radiate inside it and the beam is coupled to the sensor with little reflection. Cross-comparison with Thomas Keating power meters has shown good agreement (within 1 dB or less) between the two sensors at 1 THz.

The power at 2.7 THz was measured with a VDI-Erickson PM4 power meter. A 2.5 cm-long circular to WR10-rectangular waveguide transition was attached to the feed-horn using a standard UG387 flange. We found that the circular-to-rectangular waveguide transition did slightly improve the matching of the output beam of the 2.7 THz tripler to the sensor (our power head did not have an integrated waveguide extension like in the current series of PM4 power meters, so a piece of WR10 waveguide was needed to connect the power head to the frequency multiplier.) The multiplier chain and the VDI-Erickson power meter were placed in a vacuum chamber that was purged and then filled with pure nitrogen gas at a pressure of 0.80 bar. The powers were first recorded by the PM4 power meter set on the 2 mW scale and a calibration
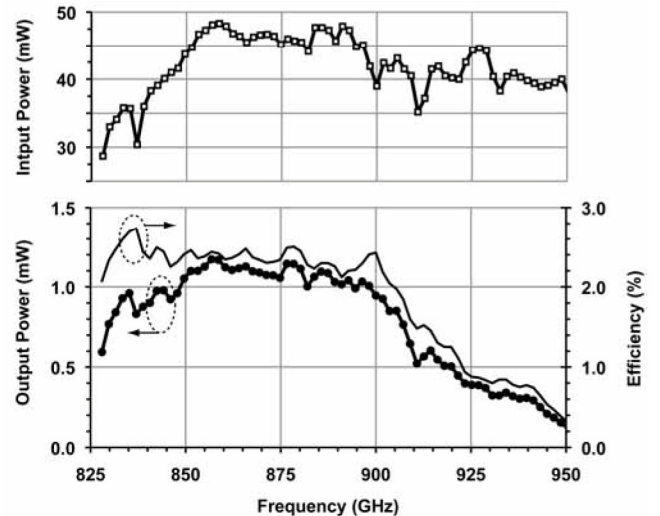

Figure 5: Performance of the first two multipliers is shown in this figure. The top plot shows the output power from the quad-chip 300 GHz tripler while the bottom plot shows the output from the dual-chip 900 GHz tripler.
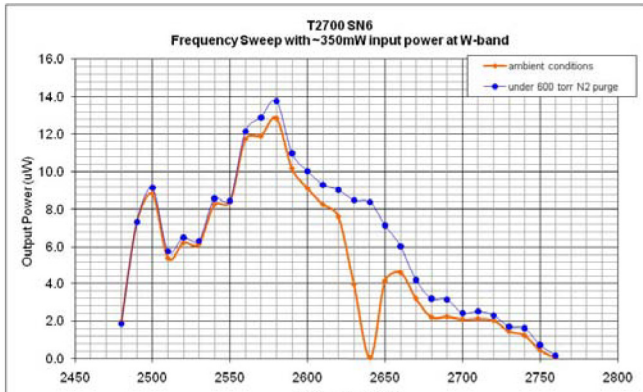
Figure 6: Performance of the LO chain at room temperature. Measured power under ambient conditions shows loss due to water absorption. In a nitrogen environment, a peak power of 14 microwatts at 2580 GHz has been measured. This is a record for a solid-state source at this frequency.

factor of 100%, and later corrected by a factor of 1.15 (0.6 dB) to take into account the RF losses of the 2.5 cm long internal WR10 waveguide and of the circular to rectangular waveguide transition [per PM4 Instructional Manual].

B. Frequency Sweep

The bias voltages of the 300 GHz and 900 GHz frequency triplers were found to be almost constant across the 2480-2750 band, and needed very little adjustment. The bias voltage applied to the 300 GHz stage was thus left constant at -12 V in all of the data presented in this paper. The voltage applied to the 900 GHz stage was set to -2 V for frequencies above 2540 GHz and between -1 V and -0.2 V for frequencies in the 2480-2540 GHz band. The input power at W-band was kept to a flat 350 mW for frequencies above 2530 GHz and was limited to 155-350 mW in the 2480-2530 GHz band due to the power roll-off of the W-band power amplifier module.

The complete chain was first characterized under ambient conditions. The measured output power is shown in Fig. 6. Even though the distance between the output horn of the chain and the waveguide of the power meter is less than 5 cm the strong water absorption line at 2640.4 GHz (strongest H_2O line in this region of the electromagnetic spectrum) can considerably attenuate the output power. The chain was then placed inside a vacuum chamber and purged and then filled with pure nitrogen at a pressure of 0.8 bars. The power meter in this setup is also placed inside the vacuum chamber. Results obtained are also shown in Fig. 6.

This chain achieved an unprecedented output power level and bandwidth for an electronic source working in this frequency range at room temperature. Peak power of 14 microwatts at 2580 GHz has been measured. A number of chains have since been built with output powers in a similar range.

IV. CONCLUSION

A compact, broadband and robust electronic source based on frequency multipliers covering the 2.5 to 2.7 THz range has been presented. Output power from this source is sufficient to pump HEB mixers in this frequency range. The performance of the chain can be further improved upon cooling and optimizing each multiplier stage if desired. The system can be adapted for network analysis, time domain studies, coherent transmitters used in laboratory spectroscopy, or as local oscillators in remote sensing.

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